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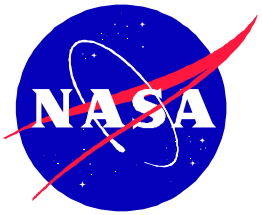


Autonomous Rovers for Mars Exploration

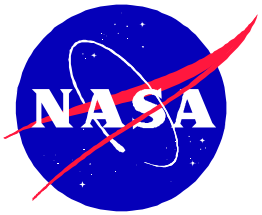
Autonomous Systems Group

NASA Ames Research Center

ASG Team Members: J. Bresina, D. Smith, R. Washington, K. Golden, V. Gupta, K. Smith, C. Anderson, and M. Smith

Key Collaborators: Intelligent Mechanisms Group at Ames

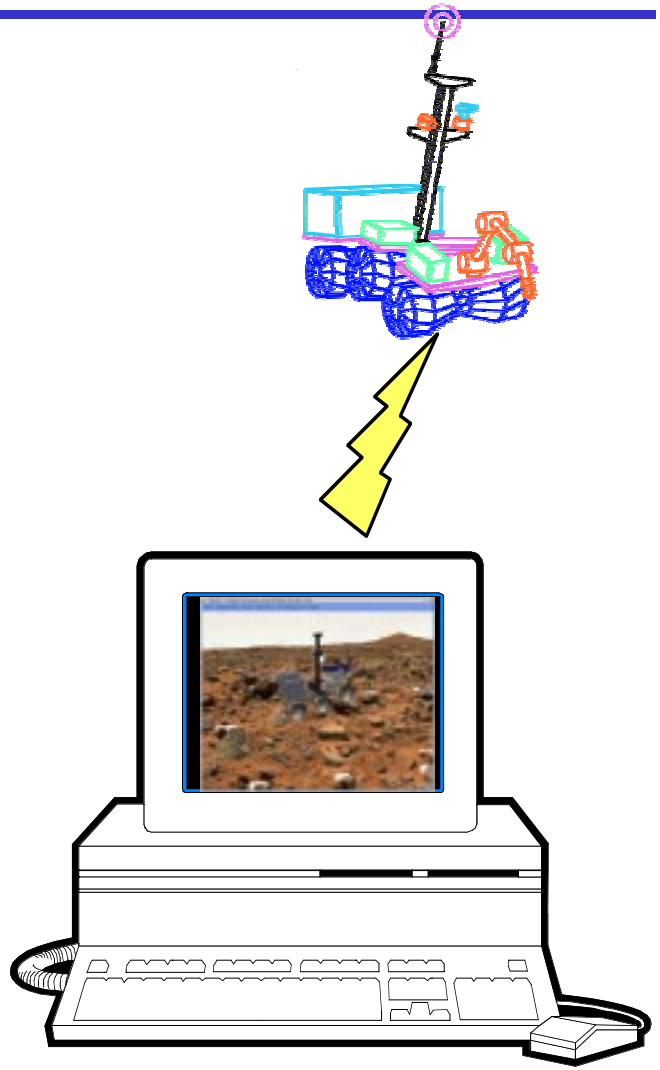
Objective & Benefits



- Overall Objectives
  - Infuse *flexible contingent sequences* into flight s/w for robust autonomous operations.
  - Advance state of the art in ground operations and onboard autonomy for planetary rovers.
- Expected Benefits
  - Increased rover productivity and science return without risk to rover safety.
  - Decreased burden on ground operations.
  - Capabilities to support human presence on Mars.

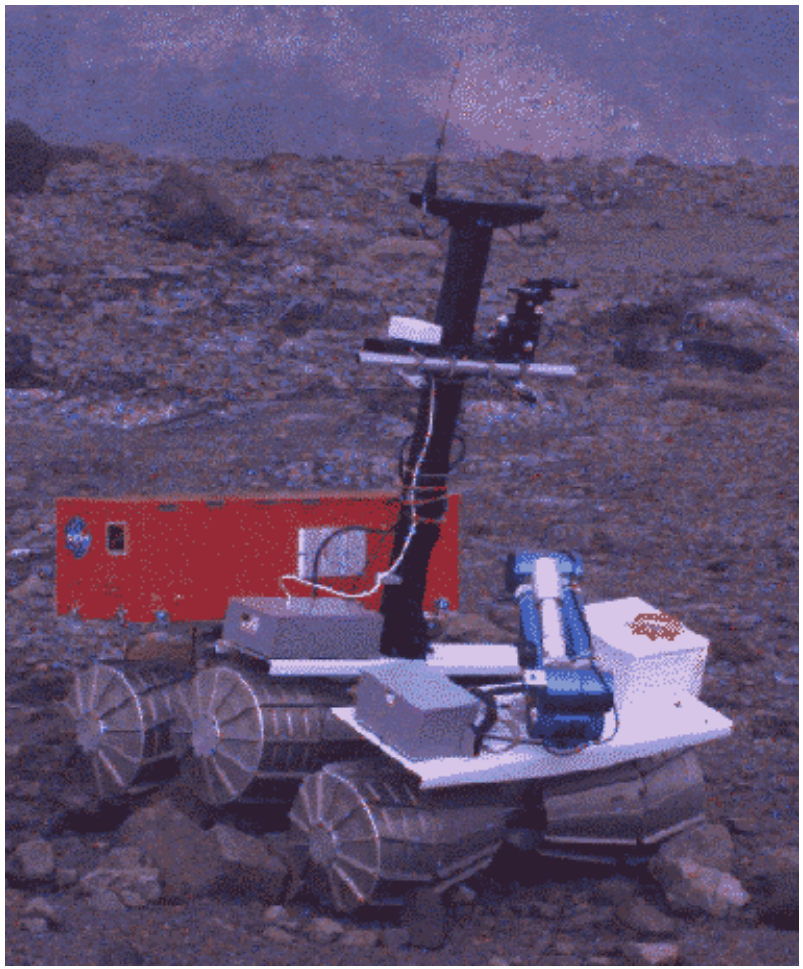
Component Technologies

- Onboard Autonomy Executive
  - Conditional Execution
  - Resource Management
  - Mode Identification & Reconfiguration
- Ground-based Support Tools
  - Contingent Rover Language (CRL)
  - Contingent Scheduling & Editing
  - Hybrid Simulation



Marsokhod Testbed

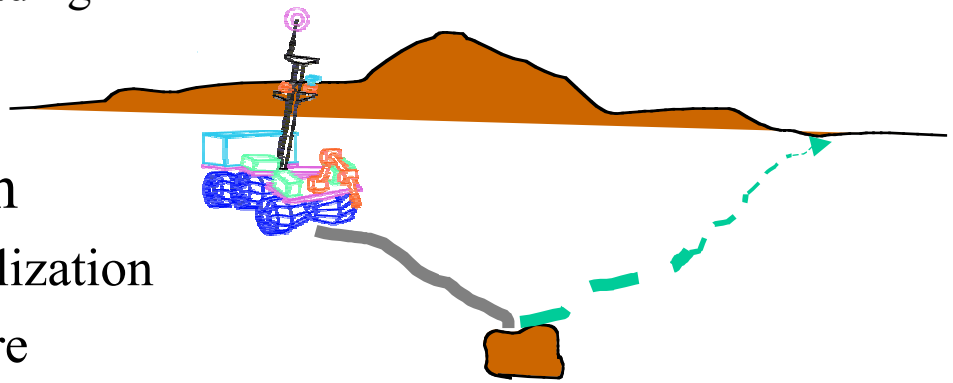
- Developed at Russian IKI
- Previous field tests in Kilauea, Arizona desert
- Vision-based navigation with stereo cameras: “visual servo”
- Science instruments: cameras, infrared spectrometer
- 3-joint robot arm
- Feb. field test in Mojave desert



Marsokhod (NASA Ames)

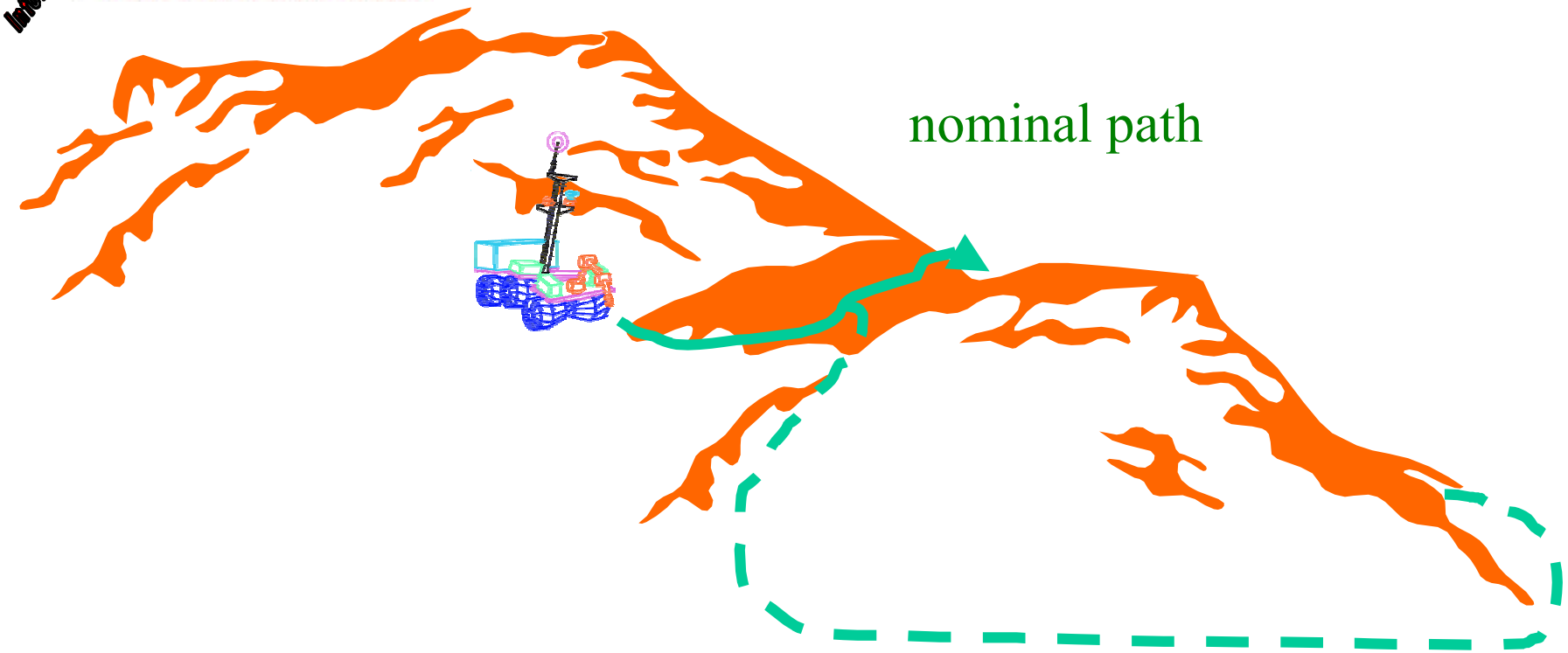
Rover Autonomy Needs

- Robust operation through flexible plans
  - Sojourner plan example:
    1. Back up to a rock
    2. Place spectrometer arm for a reading
    3. Take a series of measurements
    4. Long traverse to next rock
  - Flexible resource utilization
    - Pessimism leads to under-utilization
    - Optimism leads to plan failure



- Failure recovery
  - Shouldn't need to wait for ground control

Planned Execution Scenario



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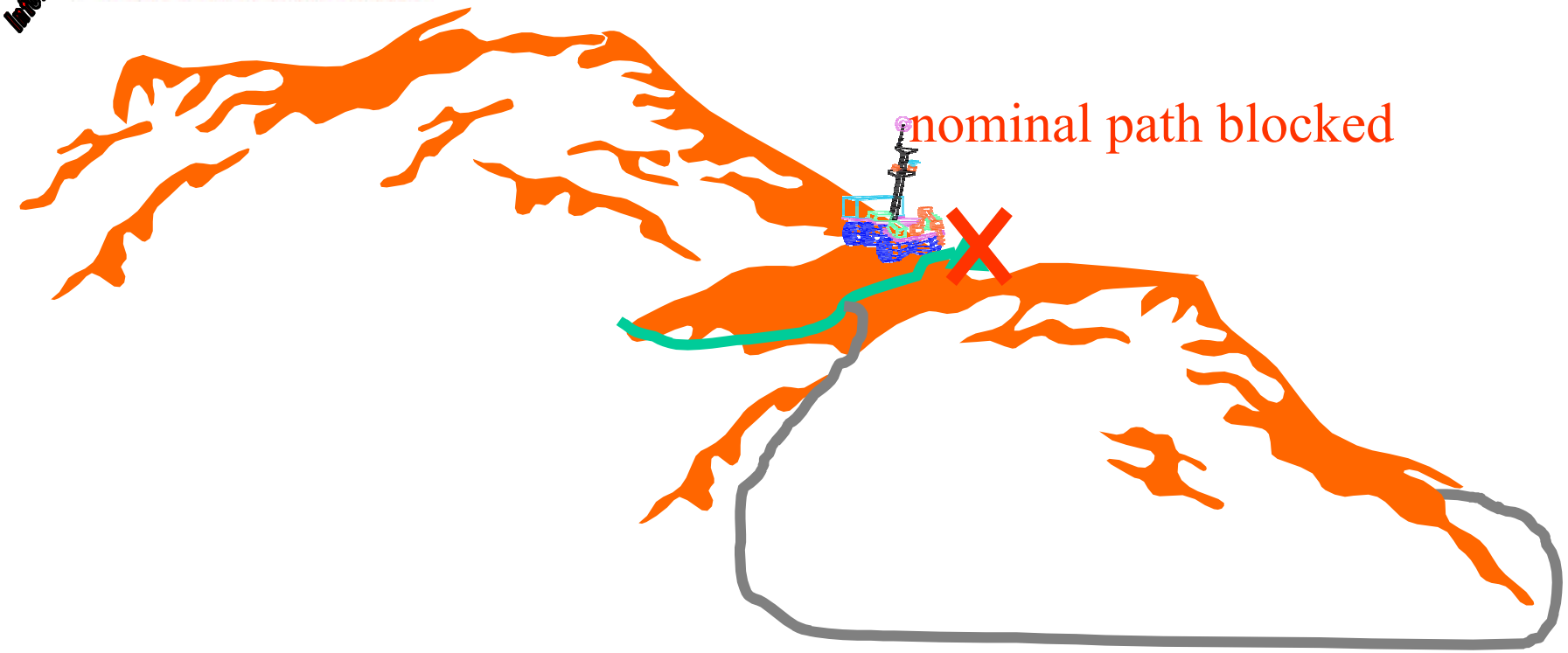
Planned Execution Scenario



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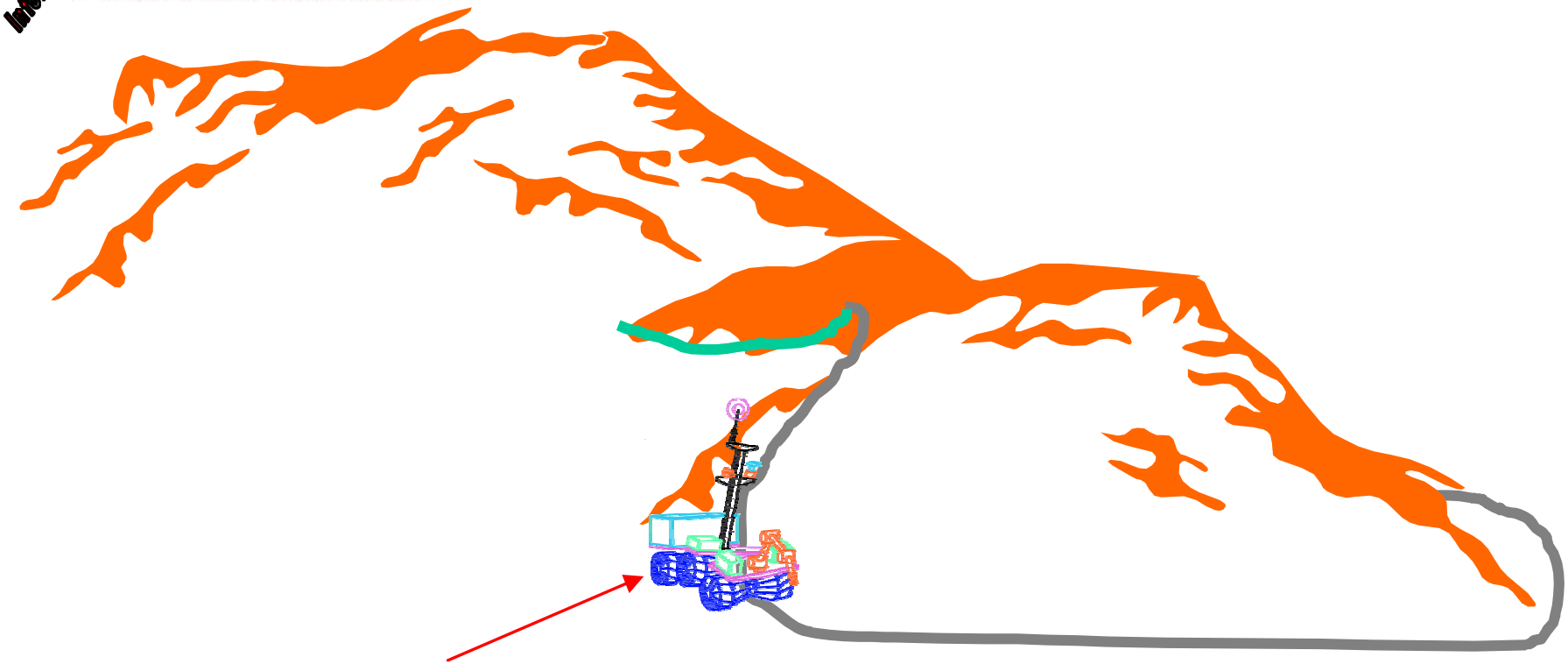
Planned Execution Scenario



wheel current too high

- stuck wheel?
- encoder failure?

execute diagnostic tests

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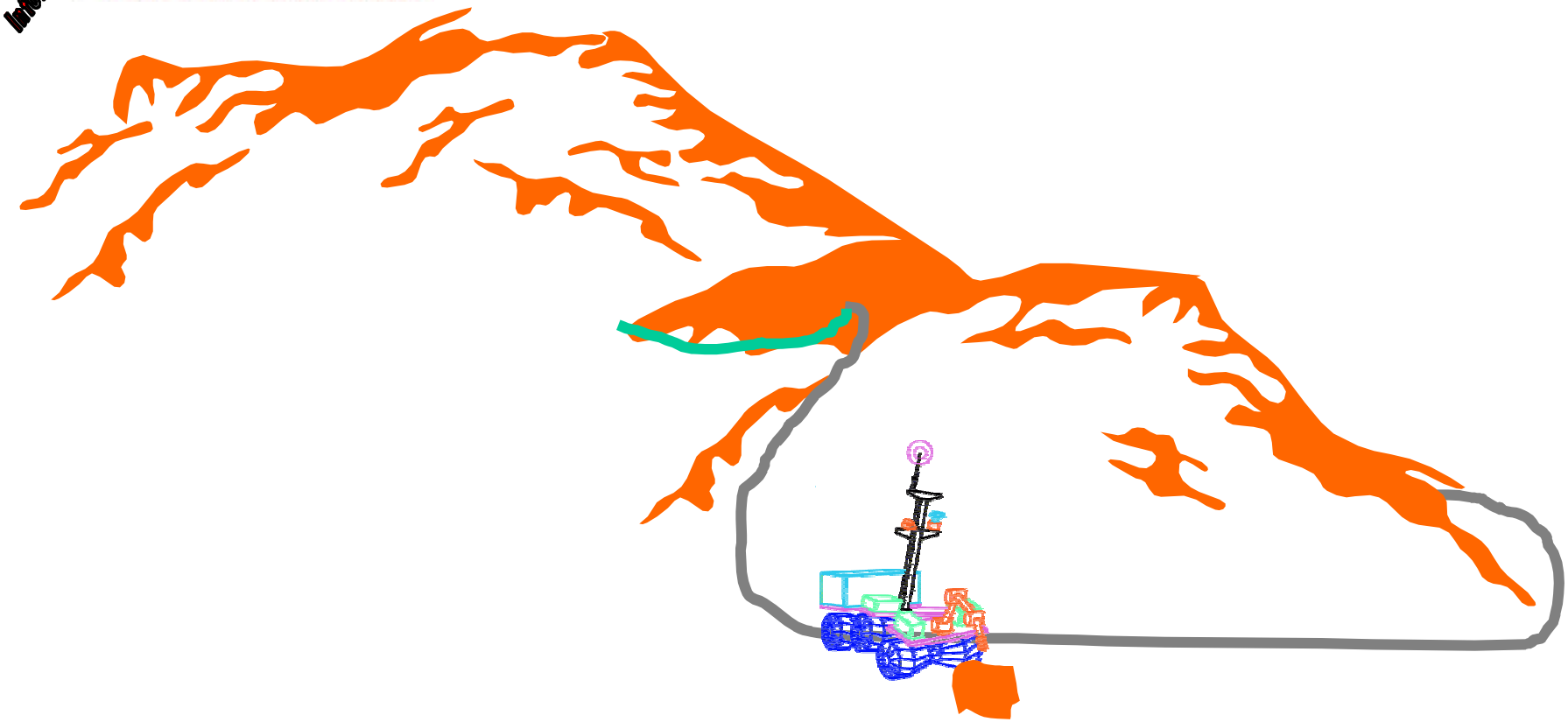
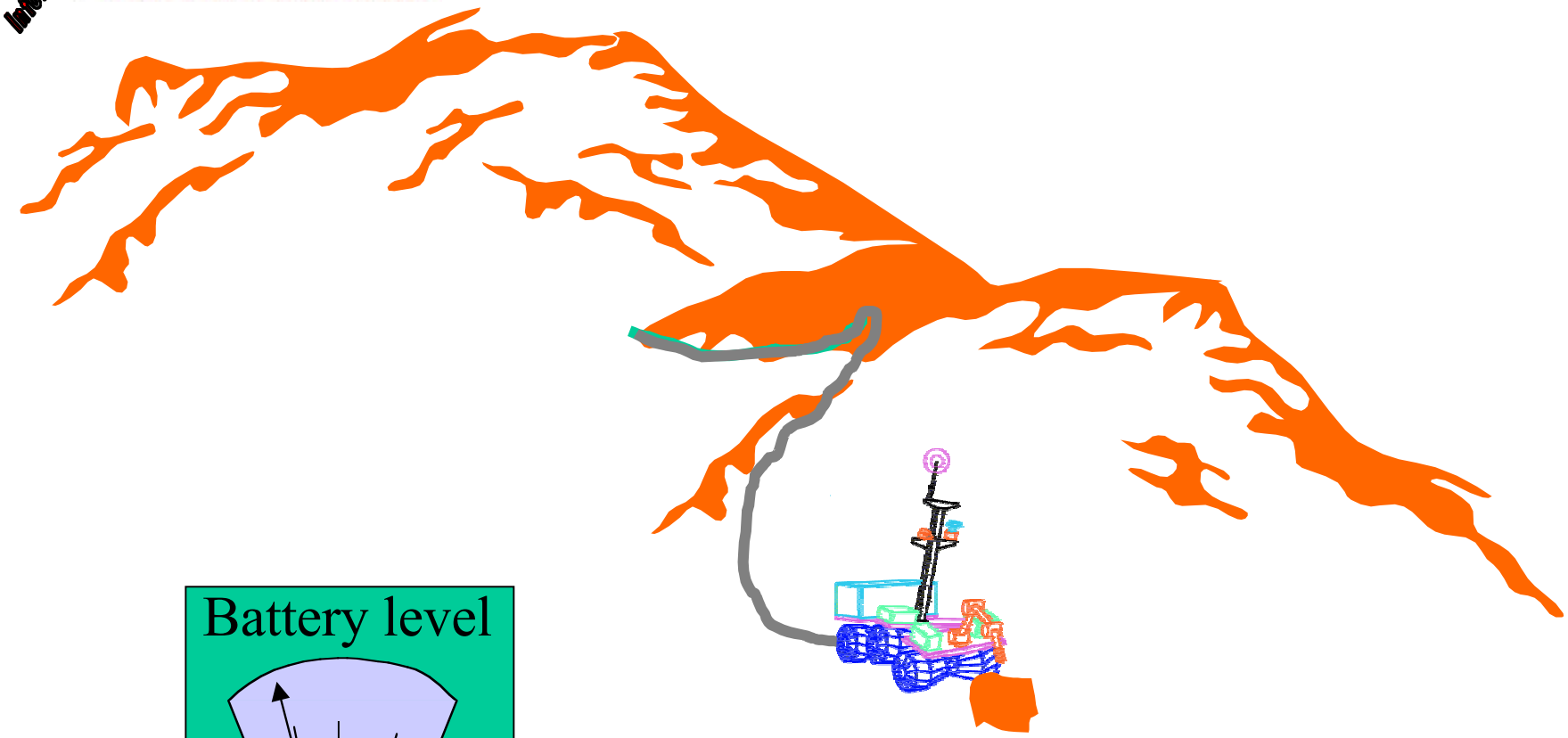
Planned Execution Scenario

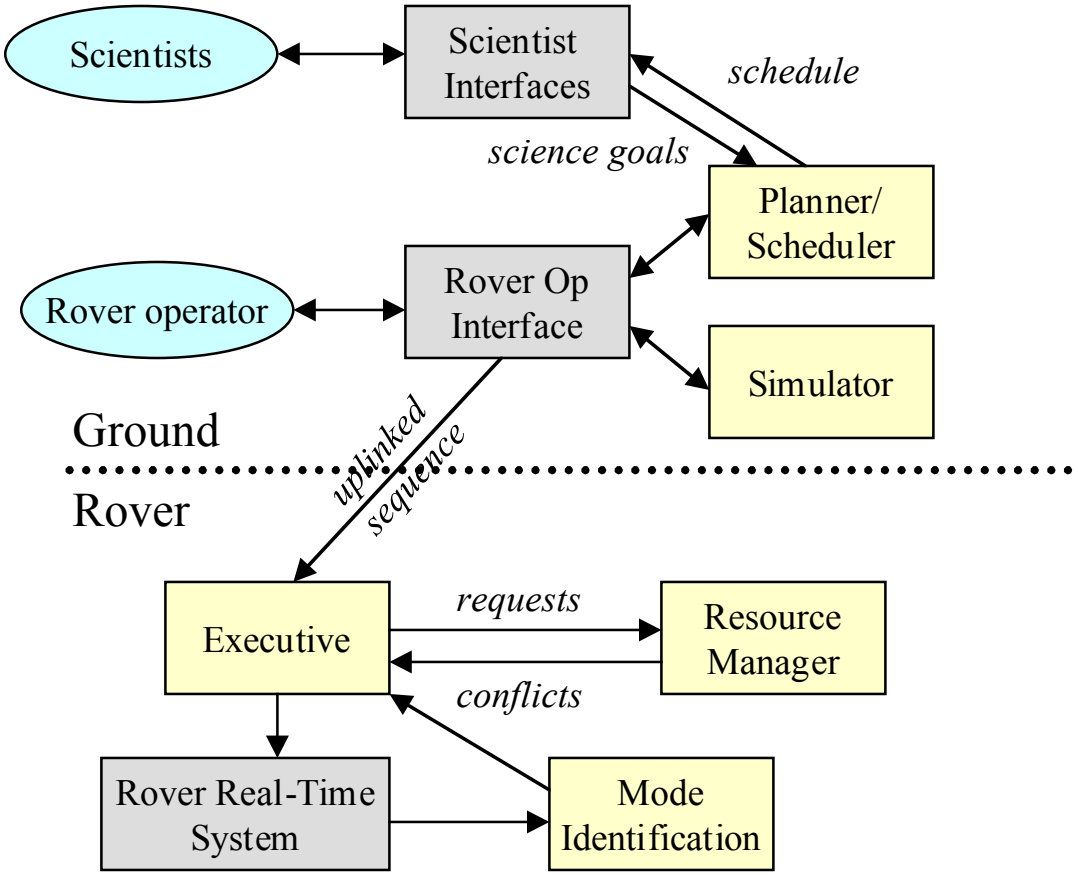


Planned Execution Scenario



abandon traverse, wait for uplink

Architecture Overview

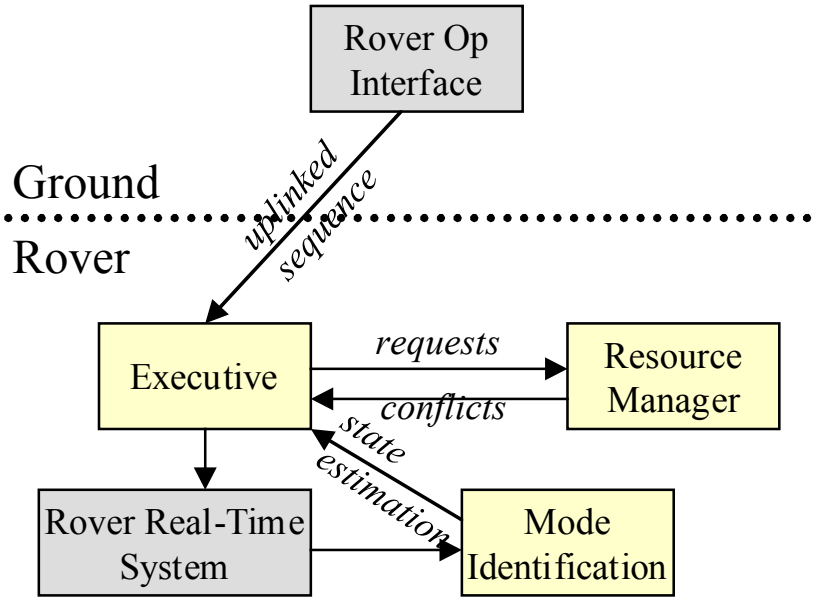


Contingent Rover Language

- Used for scheduling, uplink, execution
- Execution-time contingencies
  - Anomalous situations
  - Serendipitous opportunities
- Conditions
  - Start, maintenance and end conditions on rover state
  - Resources (power, storage)
  - Flexible time bounds
- Alternate plan library
  - Global contingent branches
  - Invoked when applicable, on task failure or task finish

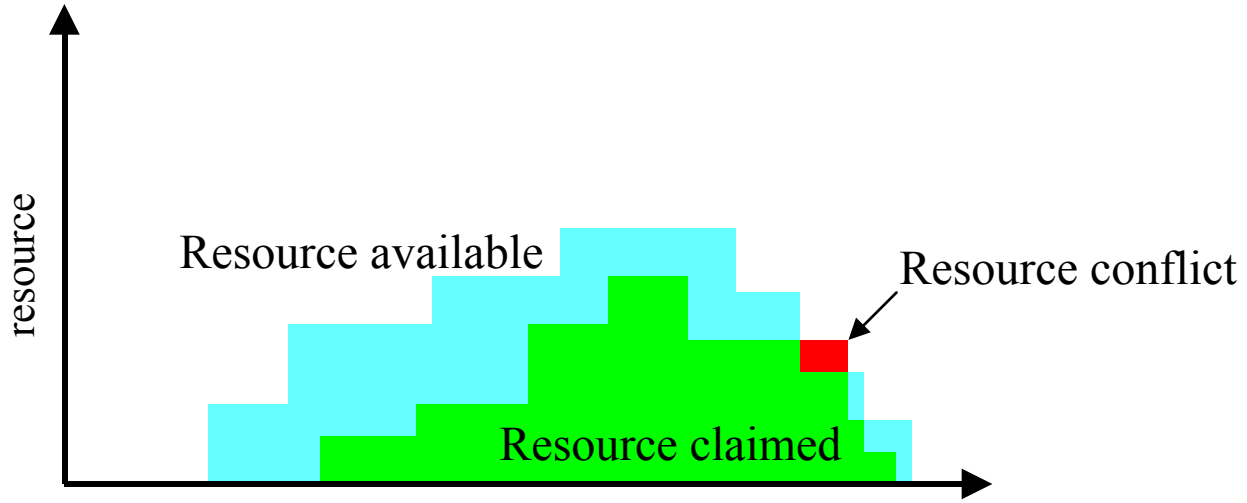
Conditional Executive (CX)

- Execute uplinked sequences
- Enforce start, maintenance and end conditions
- Respond to state/resource changes by choosing contingent branches or alternate plans

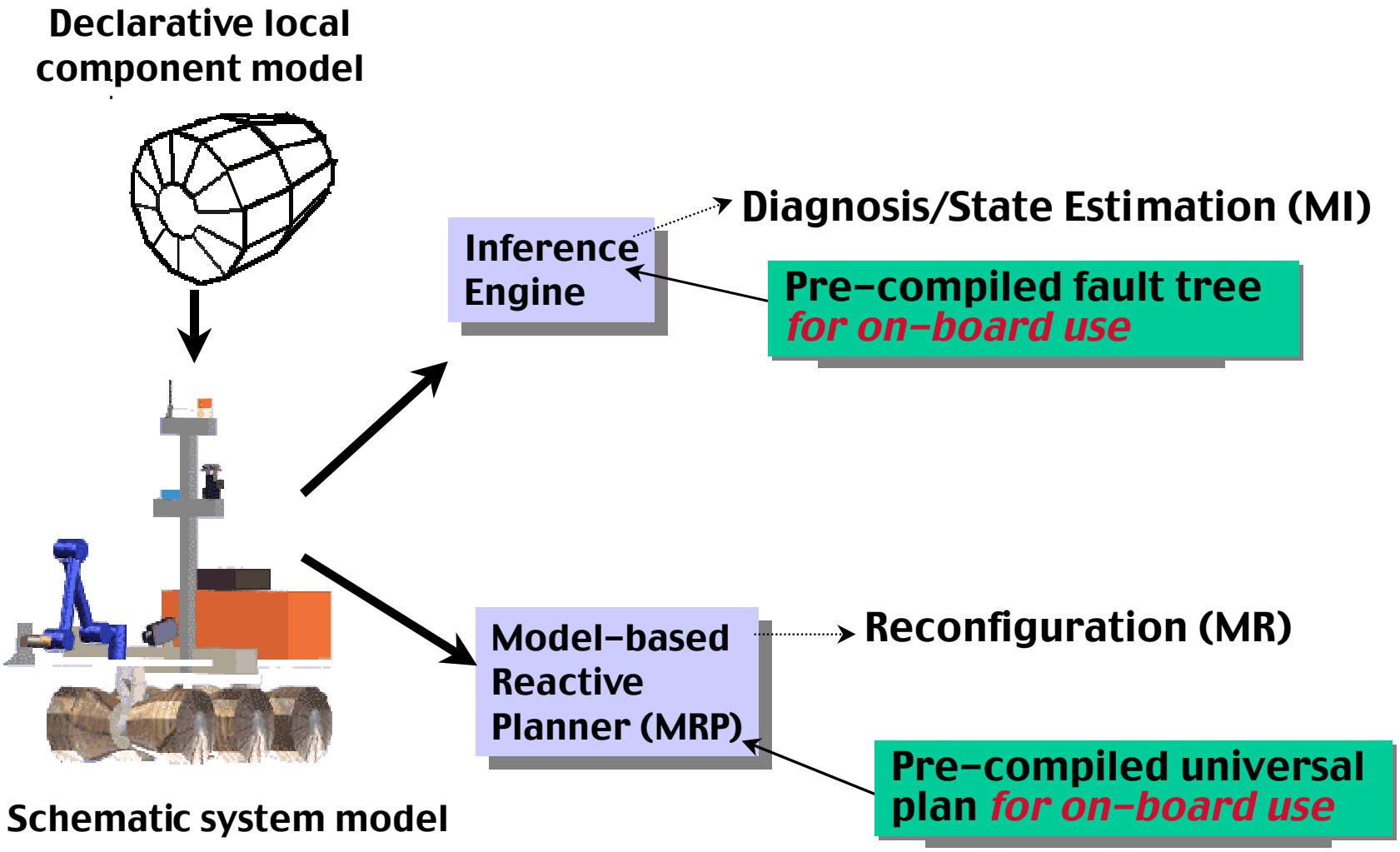


Resource Manager (RM)

- Notice diff. in predicted/actual resource availability
- Choices in plan allow the rover to adapt
  - Respond to overloading by shedding tasks or aborting the plan
  - Exploit opportunities by performing extra tasks

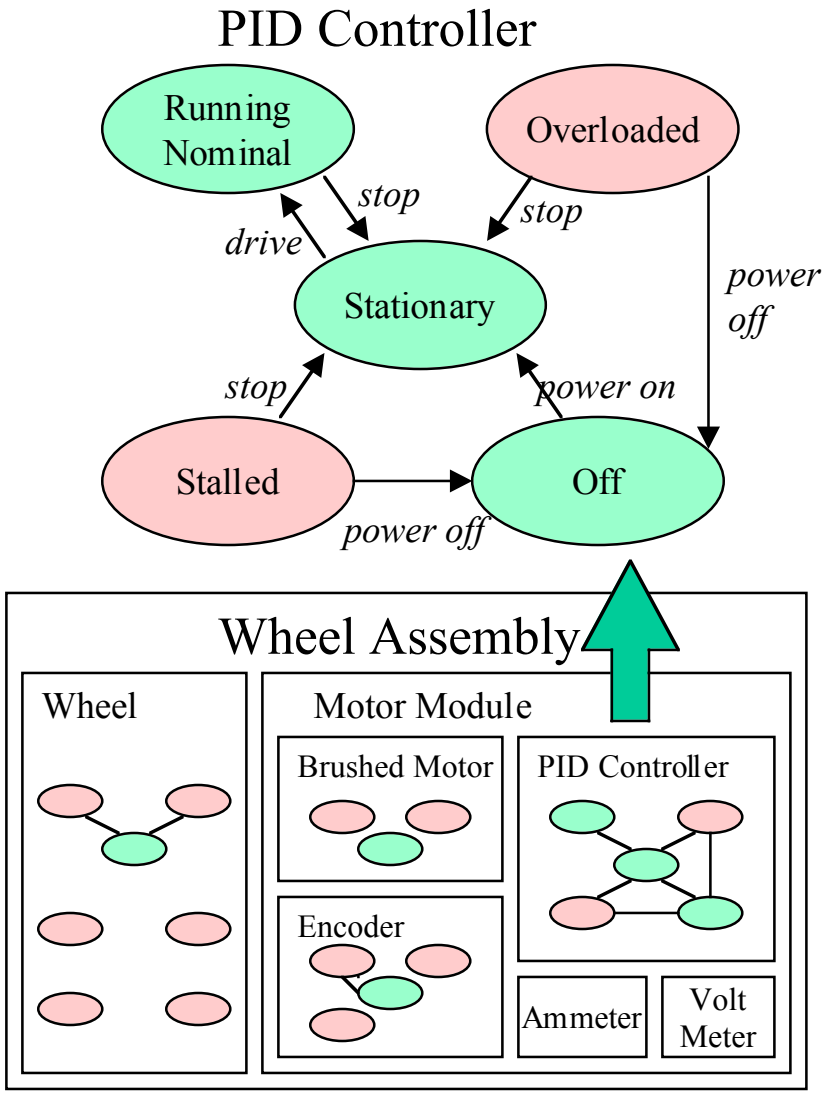


Mode ID & Reconfiguration (MIR)



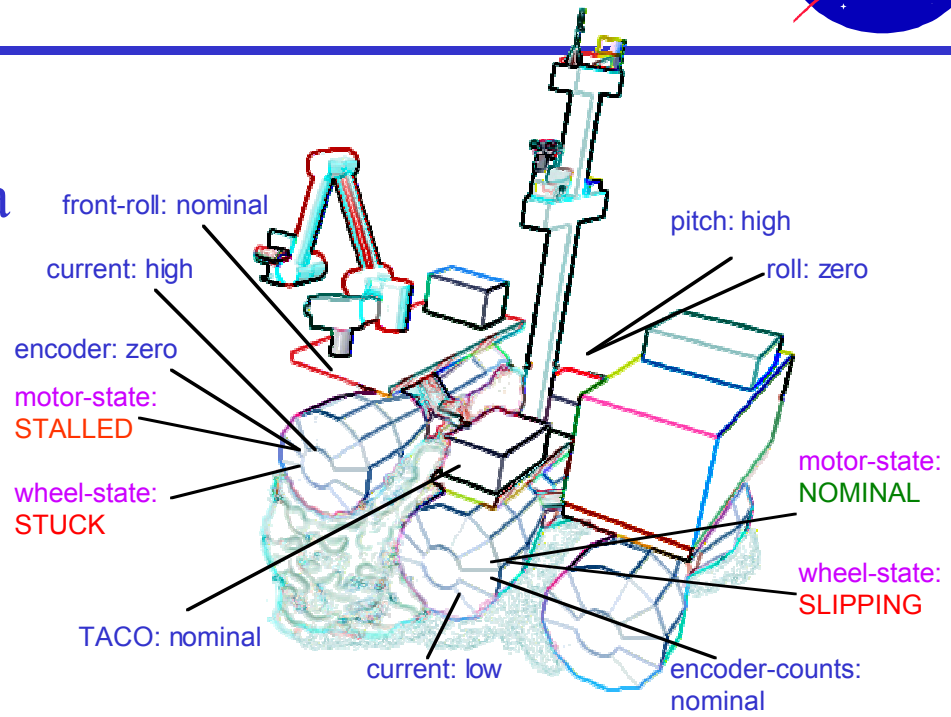
MIR Rover Model

- Model for each component represents its possible states
- Transitions shown correspond to commands
- Implicit probabilistic transitions to fault modes
- System model built up from component models
- Qualitative, modular system allows reuse of sub-models
  - Marsokhod models have been adapted to CMU's Nomad rover



Mode Identification

- Input: qualitative sensor data
  - provided by monitors
- Output: rover state
  - mode of each component
- Simulate state transitions
- Assume each component in expected (nominal) mode



- Attempt to find contradiction using deductive inference
- If there is a contradiction, find most likely set of faults consistent with sensor readings

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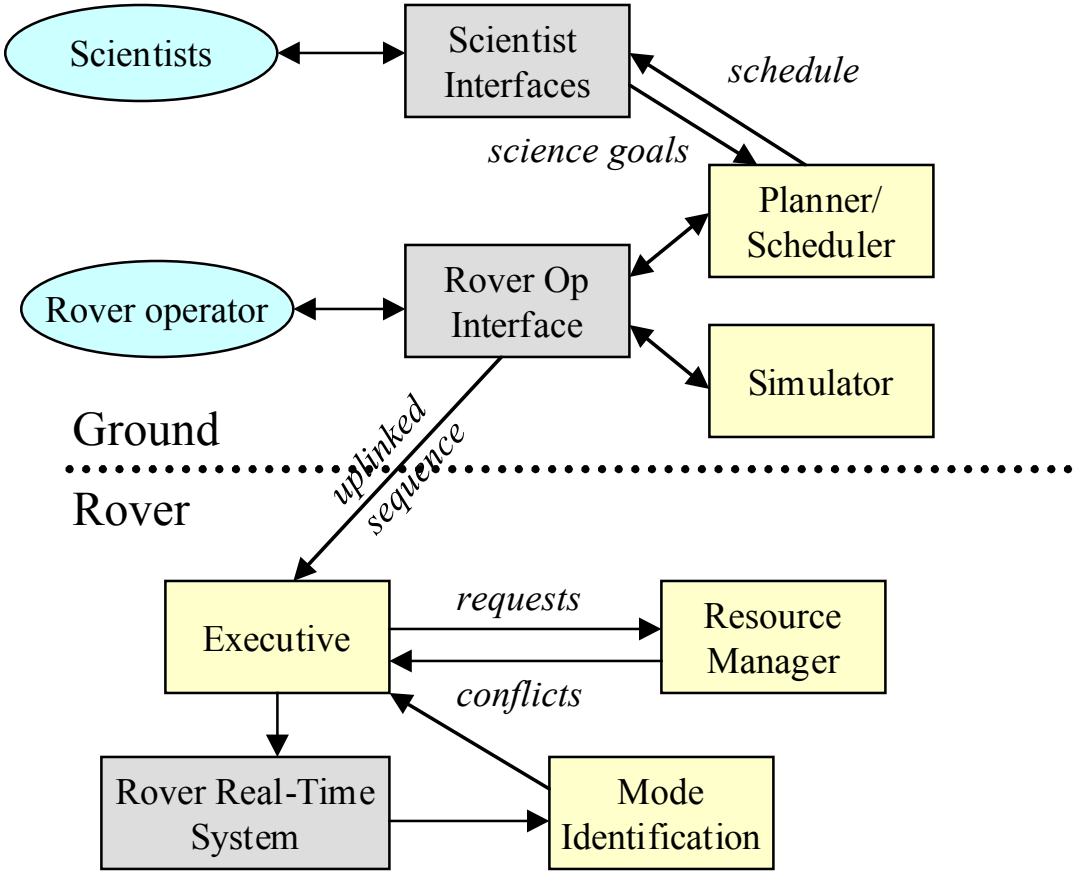
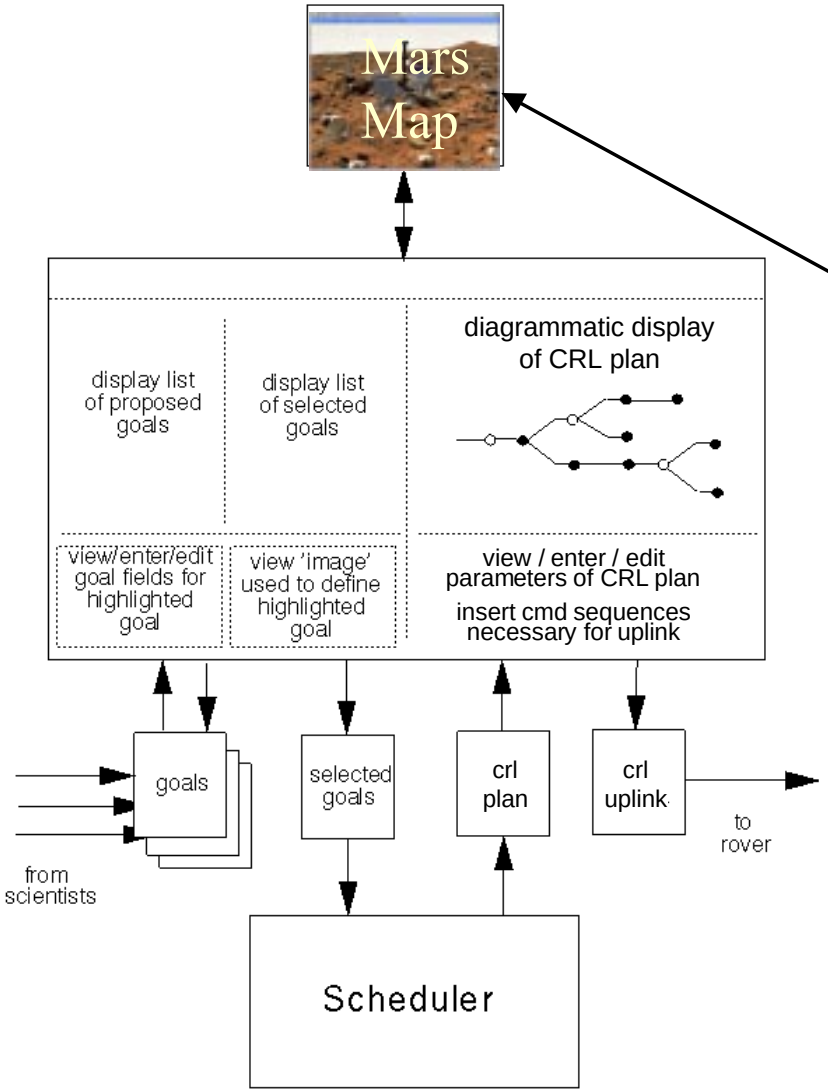
Architecture Overview



Scientist User Interface



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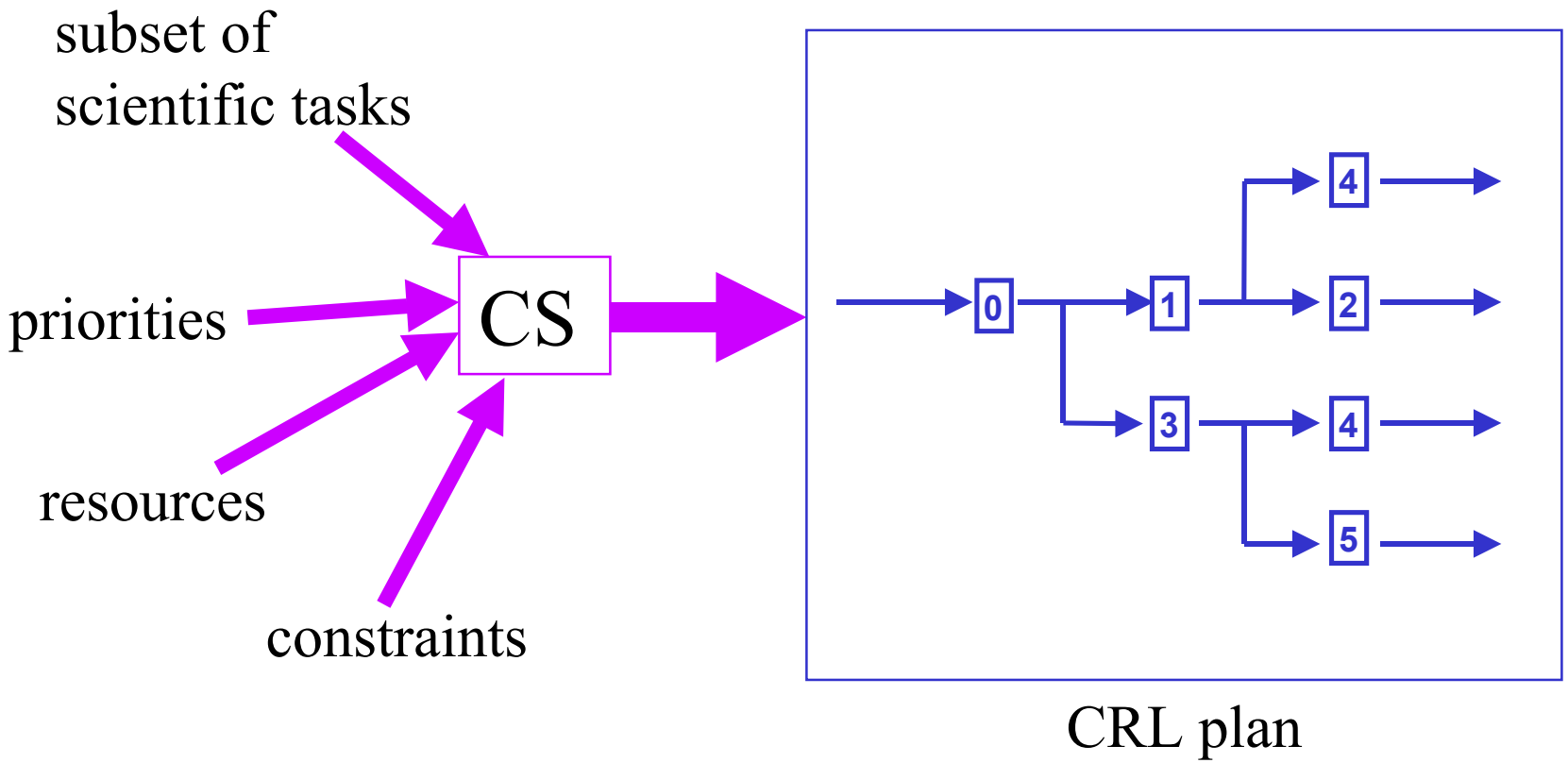
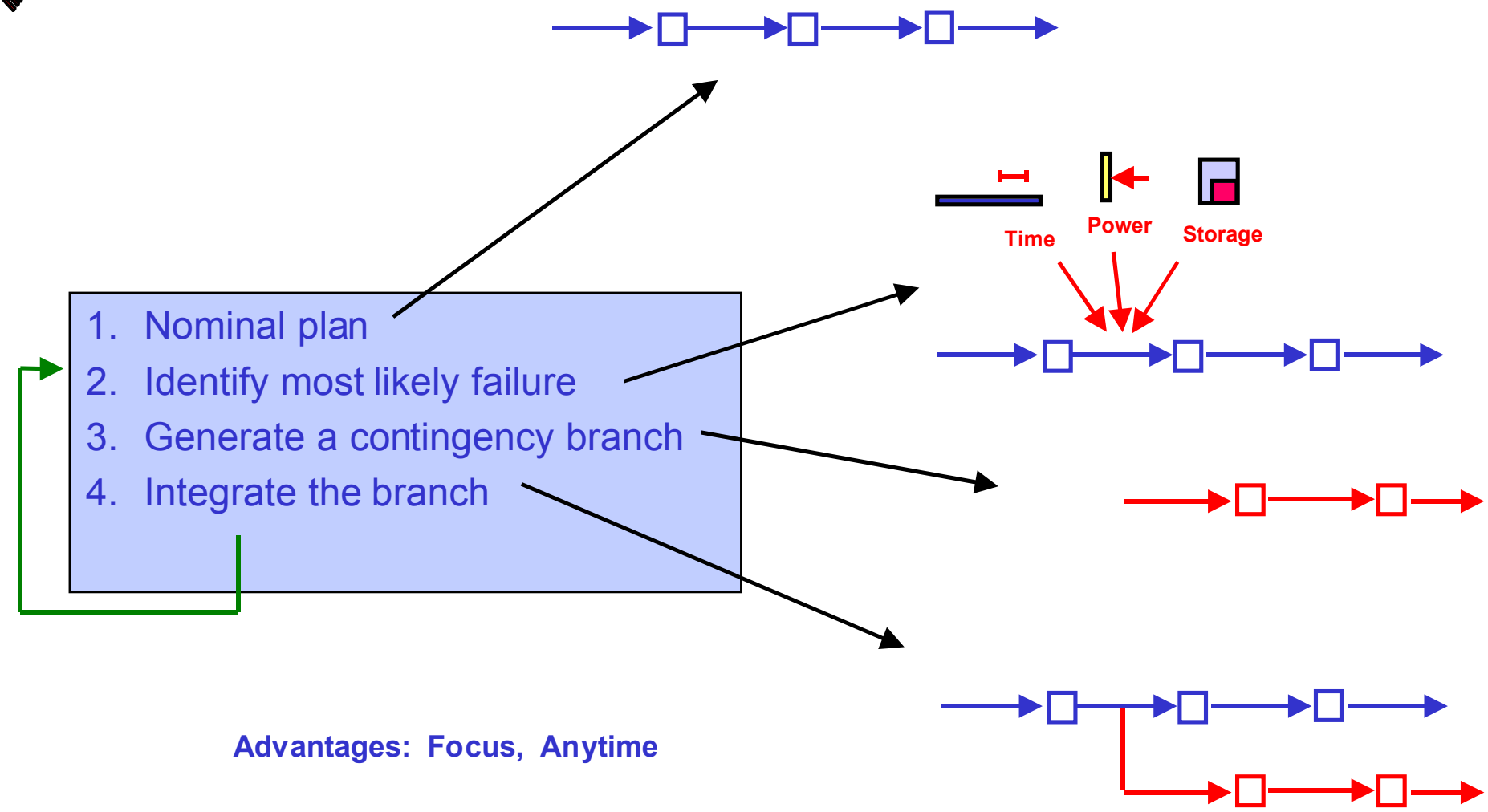
Contingency Scheduler



CRL plan

Just-In-Case (JIC) Planning



Advantages: Focus, Anytime

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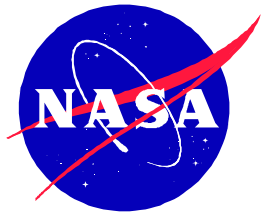
Rover Simulator

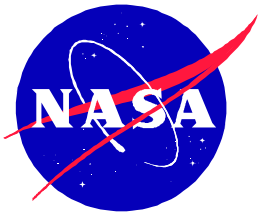


- Real-time simulator for testing command sequences and fault diagnosis.
- Models of simple rover dynamics, power systems and mechanical failures.
- Models of each component in Hybrid cc. Allows compositional description of dynamic/discrete behavior, and easy model extension.
- I/O using same message formats as rover software.
- Rover attributes are displayed in real time on scientist user interface.

Marsokhod Mojave '99 Field Test

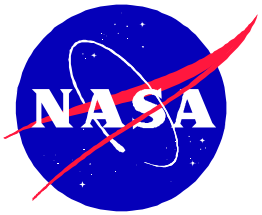
- Conducted January 28 to February 28, 1999 at Silver Lake dry lake bed in California's Mojave desert.
- Demonstrated advanced rover technologies and science investigation strategies for planetary surface operations.
- Simulated main objectives for Mars '01–'05 missions.
- Initial operational tests of end-to-end architecture.

Status



- Current status
  - Autonomy architecture deployed on Marsokhod rover
  - Initial field test in Mojave desert completed
- Next steps
  - Deployment of resource management, model-based recoveries
  - Integration with simulator
  - Further engineering tests on rover platform
  - Verification tools (constraint reasoning and simulation)
- Future directions
  - Active sensing & testing for diagnosis
  - On-board utility refinement & schedule refinement
  - Multiple threads/timelines in contingency plans

Conclusions



- Architecture extends state of the art in planetary rover autonomous operations
  - On board:
    - flexible plans
    - robust execution
    - self-diagnosis
  - On ground:
    - science/ops interface
    - simulation
    - sequence generation